An Integrated Modeling and Observational Study of Three-Dimensional Upper Ocean Boundary Layer Dynamics and Parameterizations

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LONG-TERM GOALS

This study contributes to our long-term efforts toward understanding:

- Mixed layer dynamics
- Processes that communicate atmospheric forcing to the ocean interior
- Frontal dynamics
- The interaction of finescale and submesoscale upper-ocean mixing at fronts.

OBJECTIVES

Physically-based parameterizations of vertical mixed layer fluxes in ocean models characterize turbulent mixing at length scales smaller than the layer depth, but do not address the dynamics of unresolved submesoscale horizontal mixing processes below their O(0.1)-O(10) km horizontal resolution scale. Modeling work carried out as part of this AESOP DRI has focused on surface boundary layer horizontal mixing processes in regions of significant horizontal variability, as commonly found in frontal regions. This study seeks to quantify the coupling between mixed layer vertical fluxes and the dynamics of lateral mixing by submesoscale coherent structures.

APPROACH

Resolution of 3D large-eddy turbulence in boundary layers of depth 10m< H_{ML}<100m enables model-data comparisons against measurements of turbulence and dispersion. Such comparisons can critically assess the role of mixed layer dynamics and surface-driven vertical mixing in the cascades of baroclinic potential energy into submesoscale lateral mixing processes. The Large Eddy Simulations (LES) have been done in close collaboration with E. A. D'Asaro and C. M. Lee, whose AESOP field experiments measured upper ocean mixing processes in the strong lateral density gradients of the Kuroshio and in a weaker front of the California Current off Monterey, during periods of varying wind and wave forcing (Fig. 1).

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14. ABSTRACT
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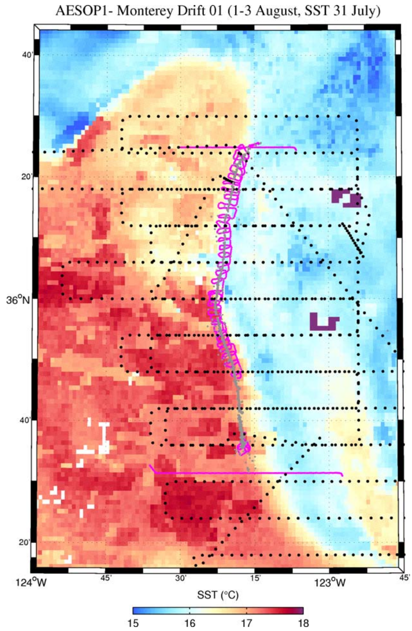


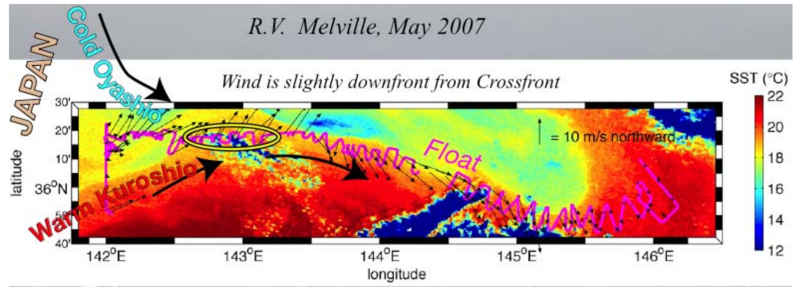


Figure 1: LES modeling has focused on two AESOP DRI field experiments, where rapid towed body surveys (magenta tracks) were used to measure the submesoscale environment of a Lagrangian float (gray tracks) deployed into a moderate strength front off Monterey (left) and a very strong frontal segment of the Kuroshio extension off Japan (above).

WORK COMPLETED

A suite of numerical simulations has been carried out for each of the two geographic field experiment components. For the California Current component, LES cases have been based a particularly well-sampled front off Monterey measured during 2006. A period of wind-driven mixing was followed by rapid restratification as the wind let up. Horizontal stratification M^2=db/dx=-6x10^{-7} s^{-2} due to gradients of temperature and salinity within the front are incorporated as uniform backgrounds in otherwise periodic realizations of the dynamics between O(1) and O(10^3) m length scales. Kuroshio case simulations are based on observations in stronger lateral density gradients (M^2=db/dx=-1.6x10^{-6} s^{-2}) where Lagrangian float measurements recorded a large departure in mixed layer turbulence energy from Lagmuir turbulence scaling. Surface forcing combined ship-based meteorological observations with surface wave spectra simulated using Wave Watch III (courtesy of NRL Monterey & FNMOC).

RESULTS

Results from simulations of upper ocean mixing in the Monterey front (Fig. 2) include:

- Rapid layer deepening occurs during downfront wind events due to ‘Ekman adjustment’ as cross-front lateral advection reduces pycnocline stability.
- Vertical turbulent kinetic energy (VKE) was unaffected by baroclinicity in both the observations and the LES of the weaker Monterey front, and consistent with Langmuir turbulence scaling (D’Asaro, 2001, Harcourt and D’Asaro, 2008).
- Horizontal scalar fluxes by 100-600m structures (Fig. 2) develop rapidly as surface-driven vertical mixing generates ageostrophic currents.
- Submesoscale lateral flux magnitudes are similar to lateral dispersion by mean vertical shear and stratification; restratification processes are also enhanced.

- Lateral fluxes are skew-directional with magnitudes that depend on the strength of vertical mixing, as well as on horizontal stratification, Coriolis, and layer depth.
- The down- and cross-gradient fluxes can be scaled together with horizontal kinetic energy.

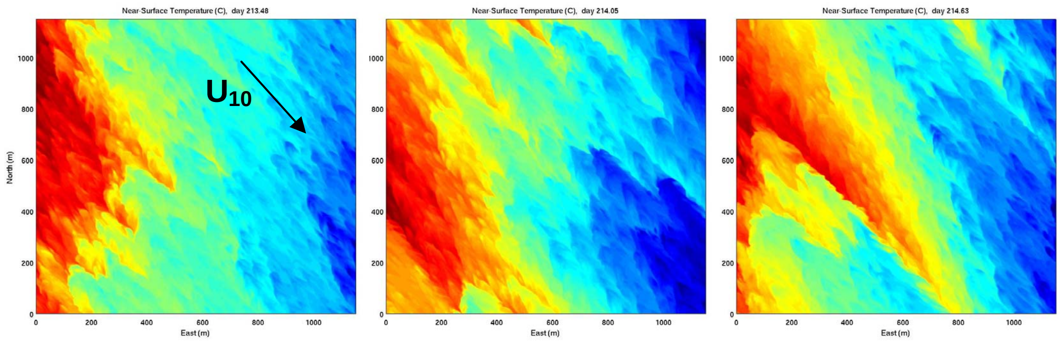


Fig. 2. LES sea surface temperature evolution over 28 hours in the Monterey front with E-W density gradient 0.0625 kg/m^3/km, while forced by wind stress and surface waves. Large horizontal turbulent fluxes are carried by the 100-600m scale structures oriented to the wind and wave forcing. These submesoscale features grow to 3-20 times mixed layer depth and the Langmuir jet spacing (still visible at O(10)m fine scales). They develop rapidly after surface forcing increases and are oriented by the surface wind stress and waves.

One advantage of the 1-D representation of the front by the profile of lateral density gradients is that such LES results can provide controlled tests of mixed layer parameterizations. This has been done for the K-Profile Parameterization (KPP) of Large et al (1994), and the intercomparison shows KPP to deepen too much when turbulence-independent Ekman adjustment dominates LES deepening. More critically, the use of KPP in lieu of resolving mixed layer Langmuir turbulence with surface wave forcing results in a significant difference in the profile of Potential Vorticity (PV).

In applying this local gradient far-field forcing approach to the stronger front case of the Kuroshio extension, a depth-varying profile of lateral density and spice gradient is imposed, corresponding in scale to that observed across this rapidly spreading front. Surface stress and Stokes drift forcing is based on a typical observed, largely cross-front wind with u*=1.2 cm/s and fully developed downwind seas. This constant-forcing LES case (Fig 3) produced strong variations in lower mixed layer stratification on inertial periods, the growth of which is limited by shear instabilities in the mixed layer base.

The w_{rms}^2 maxima in both observed and modeled mixed layer VKE represent a clear departure from Langmuir turbulence scaling ($w_{rms}^2 \sim 1.35\, u*^2$), and coincide in the model with maxima in total negative mixed layer PV. The observed duration, magnitude and uniqueness of this mixed layer turbulence production in the O(1) day observation record are consistent with the inertially periodic simulated instability. However, the growth of the instability precedes the appearance of mean negative PV on this 144x144 m^2 horizontal domain scale, indicating that the conversion of baroclinic energy to 3D turbulence begins when mean PV grows negative on a smaller lateral scale. While it is somewhat surprising to find this agreement between the observations and a model with only 1st order ingredient representation of the density field, this result is nonetheless consistent with the understanding that

symmetric or centrifugal instabilities are unstable inertial oscillations that drain baroclinic potential energy into diapycnal mixing events.

Modeling results for the moderate California Current case and the strong Kuroshio extension case are profoundly different. The growth of submesoscale features in the large domain Monterey front (Fig. 2) represents an *inverse* cascade of energy from instabilities of the front brought on by a departure from geostrophic balance by 'finescale' mixed layer turbulence. On the other hand, the phenomenon encountered in the Kuroshio extension (Fig. 3) represents *forward* cascade of energy from frontogenetic mesoscale straining through submesoscale instabilities and down into turbulent vertical and lateral mixing.

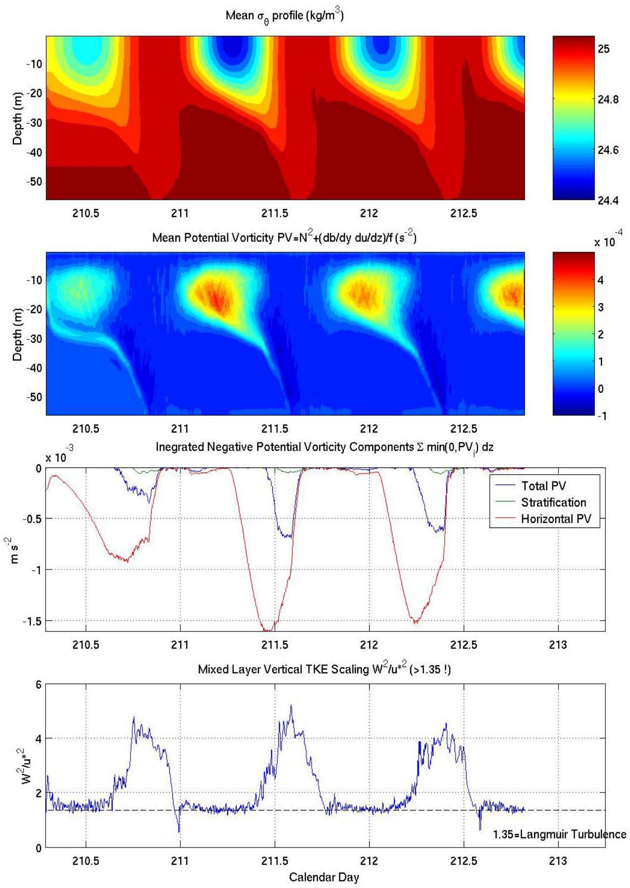
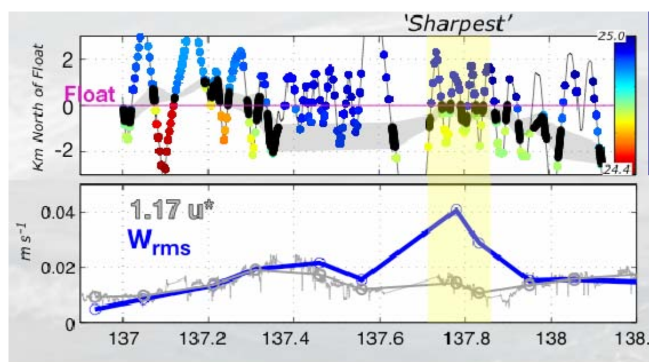


Figure 3: LES modeling of upper ocean mixing in the very strong segment of the Kuroshio extension off Japan (left panels), showing, from top to bottom: the evolution of the mean density profile within the modeled front, the mean potential vorticity (PV), vertical integrals of negative-sign PV components, and the evolution of turbulent w_{rms}^2 within the mixed layer. Field data (panels below) show the front-relative Lagrangian float position relative and the evolution of mixed layer turbulent velocity w_{rms}.



One very remarkable feature that both Monterey and Kuroshio simulations do share is that the modeled instabilities and mixing intensities depend strongly on surface forcing. Simulations of the Monterey front without the additional forcing from surface wave Stokes drift yield lateral fluxes that are reduced, in proportion to the reduction from Langmuir turbulence VKE scaling to wave-free boundary layer levels ($w_{rms}^2 \sim 0.64u^{*2}$). In the Kuroshio extension case, removing the surface wind and wave forcing produces similar inertial oscillations that do not become unstable and do not produce such bursts of TKE through shear instabilities. The lateral fluxes examined in the Monterey case are also present and stronger in the Kuroshio case, but the dependence on permitted scales (i.e. LES domain size) is not yet determined. What is particularly interesting though is that the shear instability

responsible for periodically elevating VKE simultaneously shuts down the lateral mixing by submesoscale fluctuations.

Several more Kuroshio LES cases are currently being computed to assess the upper ocean frontal evolution in response to time-dependent frontogenetic mesoscale straining. The analysis of these cases will also included assessing the role of surface wind and wave forcing in generating the instabilities and strong mixing observed at this unique site.

IMPACT/APPLICATIONS

It is useful here to note the parallel and more advanced developments in the context of atmospheric modeling since the identification of an inverse cascade, or 'Richardson scaling' regime in velocity spectra by Nastrom and Gage (1985), based on commercial flight data. Their description of an inverse cascade of energy extending up from storm scales has led to the inclusion of randomly-generated subgrid backscatter schemes, linked to the local energy loss from larger model-resolved scales and the impact of storm forcing (Shutts, 2005). While not entirely equivalent, a similar backscatter mechanism related to local EKE and vertical mixing strength may ultimately have a positive impact on future regional and global ocean models.

RELATED PROJECTS

The AESOP is officially composed of two separate DRI's covering the first three and the current final two years. AESOP results may bear significantly on the upcoming Lateral Mixing and Coherent Structures DRI.

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